Dynamic Planet C

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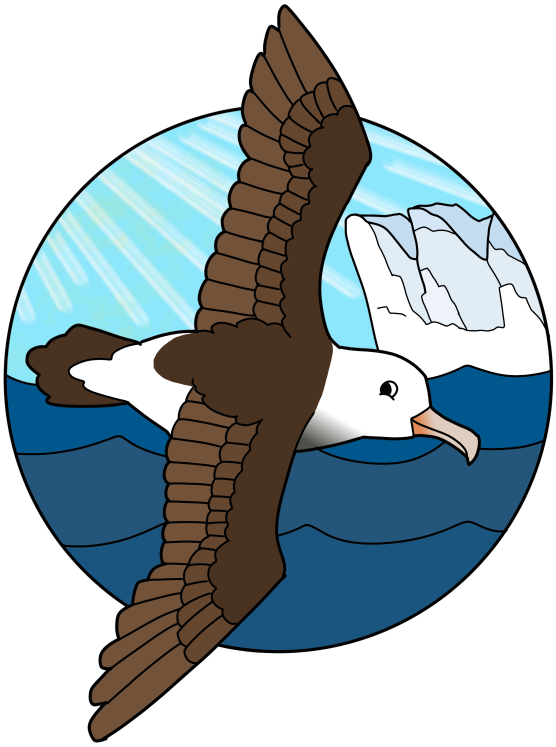
March 7th, 2021 - March 13th, 2021



Directions:

- You will have 50 minutes to complete the entire exam.
- You may use a binder, but this test is **not** open internet.
- This test is worth 330 points. It is long and not meant to be finished.
- There are 14 sections, each focusing on a different topic. It is recommended to look through all sections, as each section contains problems of varying difficulty.

Good luck!

1 Multiple Choice

1. (1 point) Which of the following layers of the ocean would have the highest water pressure?

   A. Abyssopelagic Zone

   B. Bathypelagic Zone

   C. Epipelagic Zone

   D. Hadal Zone

   E. Mesopelagic Zone

2. (1 point) At which of the following locations would you expect to find the coldest surface waters?

   A. Off the east coast of South America near Brazil

   B. Off the southeast coast of North America near Florida

   C. Off the northwest coast of Europe near Norway

   D. Off the northwest coast of Africa near Morocco

3. (1 point) An oceanographer wants to study the properties of discrete seawater samples at specific depths. Which oceanic tool best suits this purpose?

   A. Secchi disk

   B. Ekman grab

   C. Nisken bottle

   D. Echo Sounder

   E. Salinometer

4. (1 point) The highest high tide would occur during:

   A. Full moon and aphelion

   B. Full moon and perihelion

   C. Third quarter and aphelion

   D. Third quarter and perihelion

5. (1 point) Which of the following correctly orders the wave types in decreasing wave period?

   A. Tides, wind-generated waves, tsunamis

   B. Tsunamis, wind-generated waves, tides

   C. Wind-generated waves, tides, tsunamis

   D. Tides, tsunamis, wind-generated waves

   E. Tsunamis, wind-generated waves, tides

6. (1 point) Water molecules in ocean waves move in _____ motion, which is similar to movement in seismic waves known as _____.

   A. Longitudinal, P-waves

   B. Longitudinal, S-waves

   C. Transverse, P-waves

   D. Transverse, S-waves

   E. None of the above

7. (1 point) During which of the following months in the Northern Hemisphere would you expect to observe a well-developed berm and an eroded longshore bar?

   A. January

   B. March

   C. July

   D. October

   E. December

8. (1 point) An oceanographer is particularly interested in neritic sediment deposits. Which of the following sediment deposits would she NOT be interested in?

   A. Abyssal clay deposits

   B. Beach deposits

   C. Continental shelf deposits

   D. Glacial deposits

   E. Turbidite deposits

9. (1 point) A La Niña event following normal conditions has what effect on the eastern Pacific thermocline?

   A. The thermocline becomes deeper

   B. The thermocline becomes shallower

   C. The thermocline dissipates

   D. It is the same as in normal conditions

10. (1 point) Which of the following directly benefits reef growth in the tropics?

    A. Warm, nutrient-poor water in the west

    B. Cold, nutrient-rich water in the east

C. Coastal upwelling in the west

D. Coastal upwelling the east

E. Greater mixing in an ocean column

11. (1 point) A hotspot island chain is located in a hypothetical plate moving eastward. Going from east to west, order the features below.

A. Active volcanoes, atolls, barrier reefs

B. Active volcanoes, barrier reefs, atolls

C. Barrier reefs, atolls, active volcanoes

D. Atolls, barrier reefs, active volcanoes

12. (1 point) Remotely sensed radiation of a specific set of wavelengths in the red range is used to measure:

A. Nutrient abundance

B. Photosynthetic activity

C. Surface salinity

D. Sea surface temperature

13. (1 point) The average salinity difference between the Atlantic and Pacific ocean can be best attributed to which of the following about the Atlantic ocean?

A. Greater evaporation than precipitation because of landmass distribution

B. Greater evaporation than precipitation because of pressure system locations

C. Greater precipitation than evaporation because of landmass distribution

D. Greater precipitation than evaporation because of pressure system locations

14. (1 point) Select all of the following that are true of the compensation depth, which can be found around 30 meters below the surface of the ocean:

☐ Photosynthesis ceases

☐ Respiration is at its maximum

■ **Net oxygen input is 0**

■ **Within the mixed layer**

☐ Often coincides with the pycnocline

15. (1 point) Coastal environments dominated by tides likely have:

A. Shallow slopes towards the ocean

B. Deltas with few distributaries

C. Higher ebb than flow volumes

D. Low groundwater elevations

16. (1 point) Which of the following water masses contains the densest water?

A. Antarctic Bottom Water

B. Antarctic Intermediate water

C. Arctic Bottom Water

D. North Atlantic Deep Water

17. (1 point) An oceanography student doesn't follow the directions for using a refractometer for seawater measurements. Fill in the blanks to best represent this scenario: If the _____ of the water sample was higher than directed, the _____ measurement must be _____ than an accurate measurement of it.

A. Salinity; temperature; higher

B. Salinity; temperature; lower

C. Temperature; salinity; higher

D. Temperature; salinity; lower

18. (1 point) Biogenous seafloor sediments and ice sheet cores are used with oxygen isotope analysis for a period of colder climate that led the Earth to be much more glaciated than at present. Which of the following would one expect to find? Choose all that apply.

■ **Lower O16:O18 in sediment compared to warmer climates**

☐ Lower O16:O18 in ice core compared to warmer climates

☐ Higher O16:O18 in sediment compared to ice core O16:O18

■ **Higher O16:O18 in ice core compared to sediment O16:O18**

19. (1 point) Choose all of the following that would likely increase the strength of a rip current:

A. Greater angle of incidence of longshore currents

B. Fewer shore irregularities

C. Occurrence of a low tide

D. Reduced percolation of swash

20. (1 point) Latitudinally speaking, subtropical gyres have centers located where:

- ■ **Westward trade winds change to eastward westerlies in the northern hemisphere**
- ■ **Westward trade winds change to eastward westerlies in the southern hemisphere**
- □ Eastward trade winds change to westward westerlies in the northern hemisphere
- □ Eastward trade winds change to westward westerlies in the southern hemisphere

2 Properties of Water and Salinity

1. (1 point) Which of the following seawater ions originates mostly from volcanic origin?

   A. SO_4^{2-}

   B. Na^+

   C. Ca^{2+}

   D. Br^-

   E. Cl^-

2. (3 points) The TEOS-10 (Thermodynamic Equation of Seawater - 2010) gives the in-situ density of seawater as a function of which three variables?

   Solution: Conservative temperature; absolute salinity; pressure (+0.5 for each; +1.5 for if specified conservative and absolute)

3. A linearized (and much simpler) equation of state of seawater is shown below:

$$\rho(S,T) = \beta S - \alpha T \tag{1}$$

   (a) (2 points) What are β and α, respectively?

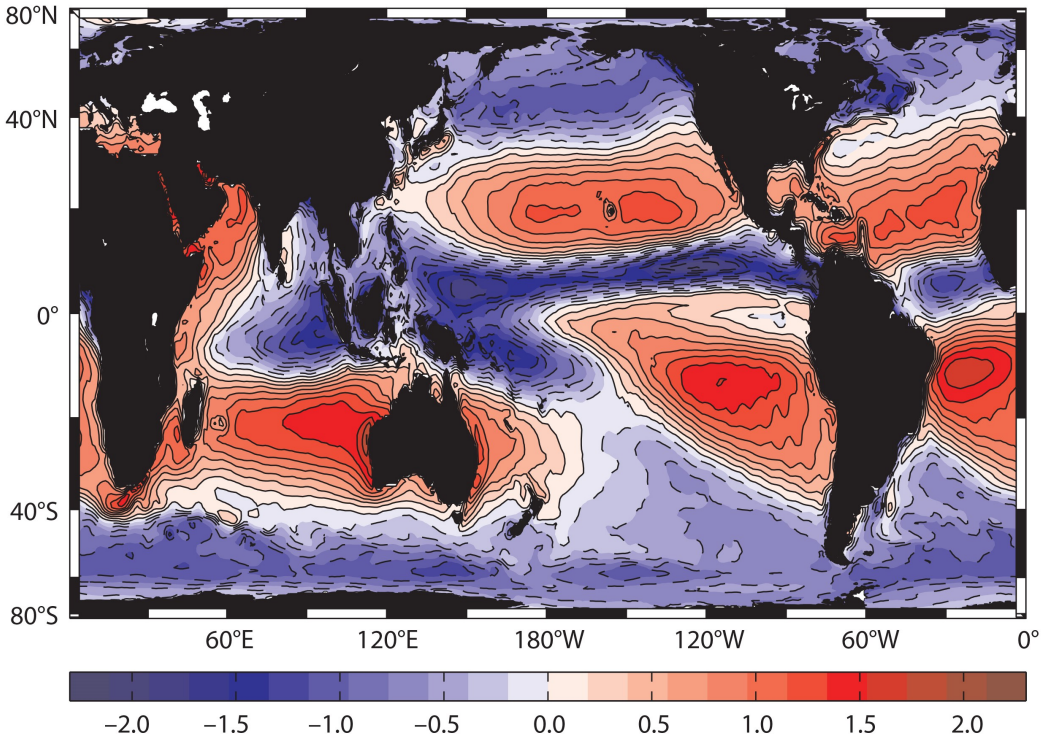
   Solution: β is the haline contraction coefficient; α is the thermal expansion coefficient (1 pt for each)

   (b) (4 points) Briefly explain why the αT term is subtracted instead of added. Why might this cause issues if α is strictly positive?

   Solution: Density decreases with increasing temperature above 4 deg C (2 pt). However, the trend is reversed for temperatures less than about 4 deg C, as that is the density maximum of seawater given a fixed salinity (2 pt).

   (c) (3 points) Why is the TEOS-10 much more complicated than this linearized equation of state? In other words, what causes nonlinearity in TEOS-10?

   Solution: As seen above, the linearized equation has issues when we assume α and β are constant. In reality, they themselves are functions of temperature, salinity, and pressure (3 pts). Hence, the true equation of state is much more complicated (it is a 75-term polynomial!)



The figure above shows a quantity plotted over the oceans.

4. (2 points) What quantity is plotted?

   A. Evaporation minus precipitation (m/yr)

   B. Salinity (PSU)

   C. Chlorophyll concentration (mM)

   D. Sea surface height (m)

   E. Sea surface temperature anomaly (°C)

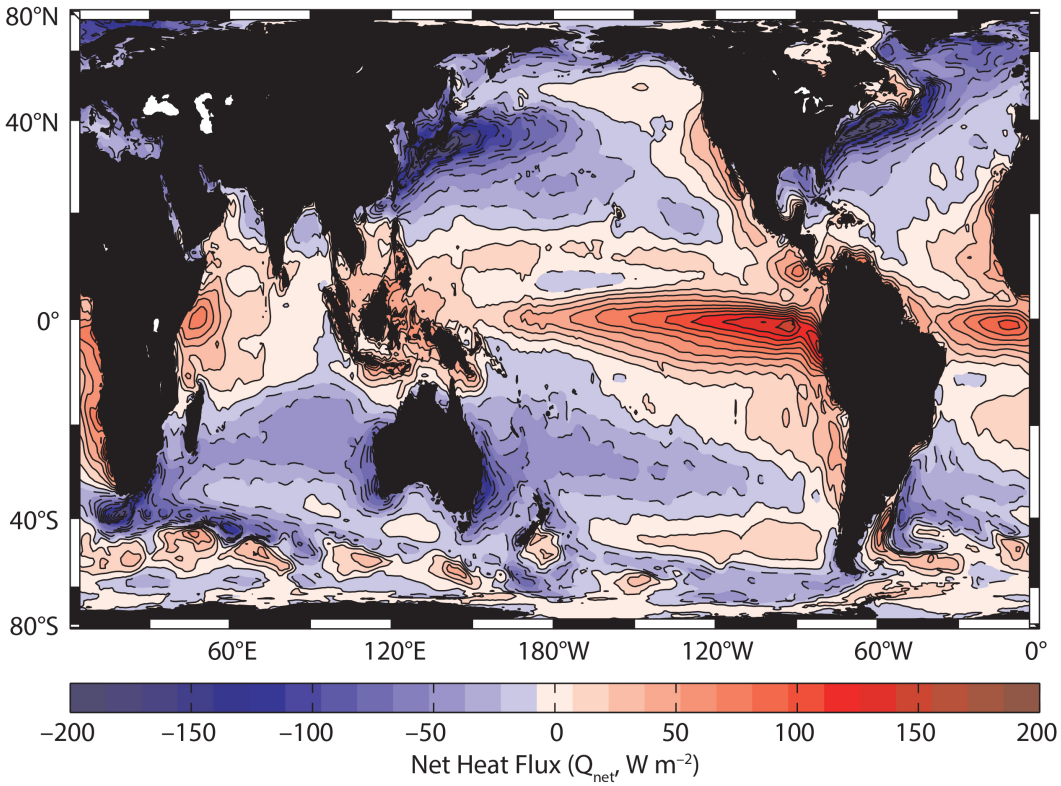
5. (5 points) Provide an explanation for the asymmetry of this quantity in the tropical South Pacific at around 10 deg S.

> **Solution:** Walker Circulation (3 pts) above the Pacific ocean causes a distinct zonal variation in the evaporation minus precipitation index. (2 pt for mentioning any sort of wind circulation, e.g. trades)

6. (7 points) Describe the general trend(s) of this quantity in a warming climate. Justify your answer.

> **Solution:** There will be greater deviation from 0; precipitation will increase in wet areas, while evaporation increases in dry areas (wet gets wetter, dry gets drier) (3 pts). As air warms, the saturation vapor pressure increases (it can hold more water) (2 pt); hence precipitation is enhanced. Radiative forcing also causes evaporation to increase (2 pt).

3 Heat Fluxes



The figure above shows the net heat flux, in W/m^2 of the global oceans.

1. (6 points) Provide an explanation for the asymmetry of net heat flux in the North Pacific. What major current is associated with the negative net heat flux in the west North Pacific?

> **Solution:** The asymmetry is simply a result of the subtropical gyre circulation that brings warm water up into higher latitudes from the equator; due to the Coriolis effect and continent topography, the western boundary current flows north (4 pts for complete explanation). Kuroshio current (2 pt)

2. (3 points) Which of the following are reasons why the heat loss in the North Atlantic is greater in magnitude than in the North Pacific?

   - ■ **Atlantic Meridional Overturning is much stronger than Pacific Meridional Overturning**
   - ☐ The Atlantic Ocean receives more heat in the tropics
   - ■ **The Atlantic Ocean is less wide than the Pacific Ocean**
   - ☐ The North Pacific is saltier than the North Atlantic
   - ☐ There is upwelling in the North Atlantic, which ventilates deep waters

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3. (14 points) Consider the heat balance of the global ocean and the data below. If the latent heat of vaporization of water is 2,260 kJ/kg, approximate the total mass of evaporated water from the ocean in a single year. (*Hint: divide solar constant by 4 to find the incoming shortwave flux*).

Average albedo of open ocean	0.06
Solar constant	1365 W/m^2
Longwave radiation emitted by ocean	100.0 W/m^2
Sensible heat loss from ocean to atmosphere	30.00 W/m^2
Total area of ocean	$3.61 * 10^{14}\, m^2$

Solution: We calculate the shortwave flux absorbed by the ocean by multiplying $(1 - a)S_0/4$ to get 320.8 W/m^2. By heat balance, we have:

Solar radiation in = longwave out + sensible heat flux + latent heat flux (4 pts)

Hence, we find latent heat flux to be 320.8 - 100 - 30 = 190.8 W/m^2 (2 pts). Next, we can rewrite W as J/s, and converting to $kJ/m^2/yr$, we find this equals $6.016 * 10^6\, kJ/m^2/yr$ (2 pts). Dividing by the heat of vaporization, we find 2662 $kg/m^2/yr$ (2 pts). Lastly, to find the total water evaporated, we must multiply by the entire area of the ocean to get $\boxed{9.61 * 10^{17}\, kg/yr}$ (2 pts)

4. (4 points) Assuming estimates for longwave emission flux and sensible heat loss are accurate, the true rate of evaporation is slightly less than what is calculated using the data above. Propose one explanation for this discrepancy.

Solution: Clouds reflect shortwave back to space before it reaches the ocean; hence the true shortwave flux "input" of the oceans is less than 320.8 W/m^2 (4 pts). Thus, we would expect the value calculated above to be an overestimation of the true value.

4 Potentially Cool

Potential temperature is a measure of temperature commonly used in both observational and theoretical oceanography. It is defined as the temperature of a water parcel if it were adiabatically expanded to zero pressure.

1. (a) (4 points) Justify where potential temperature would be most different from in-situ (i.e. measured) temperature.

> **Solution:** Potential temperature differs from in-situ temperature when the seawater pressure is significant. (2 pt) Hence, the potential temperature would be most different from in-situ temperature at the deepest depths. (2 pt)

(b) (9 points) Potential temperature may be related to the in-situ temperature by the following relation:

$$\theta(S,T,p) = T + \int_p^0 \Gamma(S,T,p)\,dp \tag{2}$$

Where θ is the potential temperature, Γ is the lapse rate of the seawater (the units are °C/m), and p is the seawater pressure. Functions of three variables may become very complicated, so we can approximate this to:

$$\theta(z) = T + \int_p^0 \Gamma(z)\,dp \tag{3}$$

Where z is the depth, in meters. Given the following seawater lapse rate,

$$\Gamma(z) = 10^{-5}(0.103z - 0.0339z^2 + 0.00432z^3) \tag{4}$$

Calculate the potential temperature of a 6.000 deg C parcel of water at 1000 m. Round your answer to 4 significant figures. (*Hint: convert p to z, a one-term approximation is sufficient*)

> **Solution:** We can take p to be a function of z: $p(z) = 0.1z + 1$. (2 pt) This is reasonable, as seawater pressure increases by about 1 atmosphere for every 10 meters of depth. Hence, we can convert $p(1000) = 101$ atm (2 pt). $dp = 0.1dz$ (2 pt). Then, we plug these back into the integral and integrate with respect to depth. We find $\theta = 6.000 - 0.972 = \boxed{5.028\,^\circ\text{C}}$ (3 pts).

(c) (1 point) ____**True**____ True/False: potential temperature is always equal to or less than in-situ temperature

(d) (2 points) Which of the following reasons explains why potential temperature may be more useful than in-situ temperature?

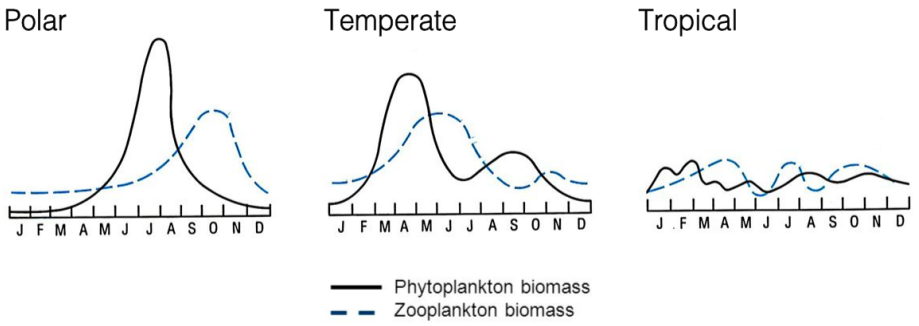
A. Potential temperature is independent of salinity, while in-situ temperature is not

B. Potential temperature is more representative of the true heat content of water

C. Potential temperature is more easily measured by deep sea arrays

D. Calculations of density involving potential temperature are simpler because salinity-dependent terms become mostly negligible

5 Plankton and Primary Productivity



The graphs above show the temporal variation in plankton biomass by latitude. Select the choice(s) that each of the following statements applies to.

1. (1½ points) Peaks in phytoplankton occur at the same time as the maximum insolation.

   ☐ Polar

   ☐ Temperate

   ☐ Tropical

   ■ **None**

2. (1½ points) The height of the phytoplankton peaks is mainly dependent on the population of zooplankton.

   ☐ Polar

   ☐ Temperate

   ☐ Tropical

   ■ **None**

3. (1½ points) Over one year, the total phytoplankton biomass produced is greater than total zooplankton biomass produced.

   ■ **Polar**

   ■ **Temperate**

   ■ **Tropical**

   ☐ None

4. (1½ points) A peak in phytoplankton biomass is created as sunlight level significantly drops.

   A. Polar

   B. Temperate

   C. Tropical

   D. None

5. (4 points) Assuming the data in all three graphs are from regions of the same hemisphere, which hemisphere do they represent? Which graph(s) from the three above may this conclusion be drawn from?

Solution: Northern hemisphere (2 pts); polar and temperate (1 pt for each without explanation, 2 pt for either with correct explanation, 0 if tropics is present; eligible if reasoning is correct even if answer was southern hemisphere); tropics do not experience significant seasonal variation.

6. (2 points) In the high latitudes, the primary limiting factor(s) on plankton biomass is/are:

   ■ **Sunlight, because little to no sunlight reaches the high latitudes much of the year**

   ☐ Sunlight, because it warms the water and increases the rate of decomposition

   ☐ Nutrients, because high latitude water is already depleted during transport

   ☐ Nutrients, because nutrients are less soluble in the cold waters of the high latitudes

7. (3 points) Although surface waters in temperate regions have abundant nutrients during one portion of the year, a sharp nutrient decrease takes place around March-April. Identify all of the following that occur around the March-April time frame and contribute to this phenomenon.

   ☐ Dissolved oxygen levels increase in the photic zone

   ■ **Density rapidly increases with depth**

   ■ **Increased insolation warms surface waters**

   ☐ More biomass begins to decay

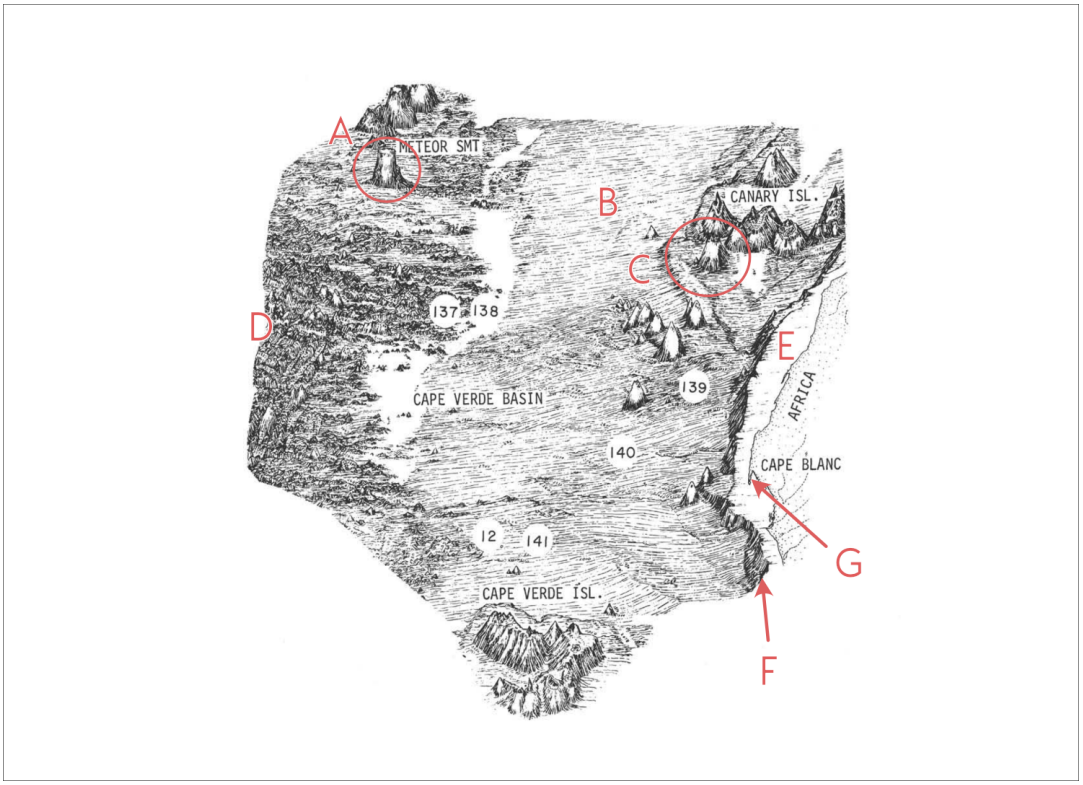
   ■ **Phytoplankton biomass rises**

   ☐ Zooplankton biomass rises

8. (6 points) If the graph for the tropics represented a smaller portion of the ocean that is closer to the meteorological equator, how might the graph change? Describe the processes that would lead to this change.

Solution: Overall plankton biomass would increase (1 pt), so the graph would be translated upwards (1 pt) without significant changes in the amplitude or incidence of its small peaks (1 pt). Near-equator regions exhibit upwelling due to Ekman transport to the north on the northern side and to the south on the southern side (3 pts).

6 The Classic Feature ID



Above is a vertically exaggerated illustration of the ocean floor adjacent to the west coast of Africa.

1. (14 points) Match each of the following descriptions to one of the letters A-G. Note that B and D refer to broad regions while other letters refer to more specific features. Disregard numbers.

   (a) **B** Composed of sediment that had traveled through submarine canyons

   (b) **D** Typically has much less relief than in this particular map location

   (c) **A** Height determined by surface wave wavelength

   (d) **G** A direct result of longshore drift

   (e) **C** Namesake feature of the surface current that flows here

   (f) **F** Has an average steepness of about 3°

   (g) **E** Salinity composition most influenced by fluvial influx

7 Coasts and Plovers

1. (4 points) Snowy plovers are small shorebirds that nest on sandy beach berms. For a nesting population on the California coast, select all of the following that are accurate about how beach sedimentation affects their breeding habitat:

   ☐ The damming of a river to the south would decrease sediment supply to the nesting grounds

   ■ **Building a jetty immediately north of the nesting ground would increase its erosion**

   ■ **In the summer, the strength of swash is greater than the backwash**

   ☐ On average, beaches are wider during the winter and narrower during the summer

   ☐ Beach nourishment is a fairly long-term method of countering erosion

2. (2 points) Which of the following types of estuaries is least likely to be found where the plovers nest in California?

   A. Bar-built

   B. Coastal plain

   C. Fjord-type

   D. Tectonic

3. (2 points) Provide an explanation for your above answer.

Solution: Mountains near the California coast cannot support alpine glaciers, so any fjords would be rare. Additionally, California is located farther south than the southernmost extent of the ice sheets from the last glacial period (2 pts).

Depth (m)	Estuary A Salinity (ppt)	Estuary B Salinity (ppt)
0	15.0	15.0
5	15.1	19.2
10	15.4	24.8
15	15.8	25.9
20	16.3	27.1
25	16.6	28.7

Data collected at varying depths in columns from two estuaries, A and B, are shown in the table.

4. (5 points) Compare the orientations of isohalines in A and B if they were to be plotted in a longitudinal (90° from cross sectional) view with the river mouth on one side and the ocean on the other.

Solution: Isohalines in A are more or less vertically oriented (2 pt). In B, isohalines slope more angled (2 pt). (1 extra pt for dip direction of isohalines in B)

5. (2 points) Estuary A is best described as _____, while Estuary B is best described as _____.

A. A salt wedge; partially-stratified

B. Partially-stratified; unstratified

C. Partially-stratified; a salt wedge

D. Unstratified; partially-stratified

E. Inverse; inverse

6. (5 points) Is Estuary A or B likely to be greater influenced by tides? Explain your reasoning.

Solution: A is more likely tidally influenced (2 pts), as seen through its well-mixed waters lacking layers stratified by salinity (3 pts).

7. (5 points) Coasts often experience local winds that blow on or offshore. The direction of these winds is based on the different warming/cooling rates of air over land and water. Describe a relevant property of water, as compared to land, and how it accounts for the temperature difference.

Solution: Water has a higher heat capacity than materials on land (2 pts), and so changes in temperature are less than land with the same energy input/output from shortwave and longwave radiation, respectively (3 pts).

8. (5 points) What is the effect of an offshore wind on a coinciding low tide? Explain why this usually occurs at certain times of the day.

Solution: Offshore winds decrease the height of the low tide at the shore (2 pt). This most often occurs after nightfall when air over land cools more than air over water, and the higher pressure over land drives windflow towards the ocean (3 pts).

9. (6 points) Like many birds, snowy plovers forage most actively in the morning, and it is suggested that the success of foraging increases as more of the intertidal zone is exposed. Using your answer from the previous question, evaluate whether or not the offshore wind/low tide interaction is likely advantageous for the plovers.

Solution: If previous question was correct (2 pts): The plovers probably will not benefit from offshore winds making low tides lower (2 pts). While more of the intertidal zone is exposed, it takes place during the night and plovers are not foraging at that time (2 pts).

Alternative answers, only applicable if consistent with previous question: 1) The plovers will not benefit from offshore winds making low tides higher (2 pts); less of the intertidal zone is exposed (2 pts); 2) The plovers will benefit from offshore winds making low tides lower (2 pts) in the morning when they forage most (2 pts)

10. (2 points) The sand that the plovers nest in may eventually become a part of sandstone beds. If we were able to observe the evidence of a transgressive sequence that takes place starting from the present, what would we expect to find above these sandstones?

A. Greater abundance of sandstones from relative sea level rise

B. Greater abundance of shales from relative sea level rise

C. Greater abundance of sandstones from relative sea level fall

D. Greater abundance of shales from relative sea level fall

8 Mid-Ocean Ridges

1. (1 point) **T** True/False: Different segments of the mid-ocean ridge can spread at different rates.
2. (1 point) **T** True/False: The Mid-Atlantic ridge contacts more transform boundaries than convergent boundaries.
3. (1 point) **T** True/False: The ocean tends to deepen with increasing distance from a ridge.
4. (2 points) Sediments in the region along the mid-Atlantic ridge are dominated by calcareous ooze while the adjacent abyssal plains are dominated by red clays. What would be the best explanation for this distribution?

   A. Red clays tend to settle in abyssal plains rather than on the ridge

   B. Calcareous fauna are more concentrated along the ridge

   C. The ridge occurs at a depth where water is saturated with CaCO3

   D. Red clay minerals are not stable above a threshold depth

5. (4 points) Provide an argument **against** each of the following:

   (a) (2 points) The age corresponding to a certain distance from a spreading center can be determined solely by counting the number of magnetic reversals detected within that given distance.

   Solution: Time intervals between geomagnetic reversals are not constant, so neither are the widths of the bands they create in the crust. Spreading rate also may not be constant.

   (b) (2 points) If the age is known at some distance from the spreading center, there is enough information to determine age at the same distance across the opposite side of the spreading center.

   Solution: Diverging plates do not necessarily spread symmetrically.

6. (4 points) Select all of the following sources of water that contribute to the output of hydrothermal vents at mid-ocean ridges:

   ■ **Percolated sea water**

   ■ **Magma**

   ☐ Sulfide precipitation

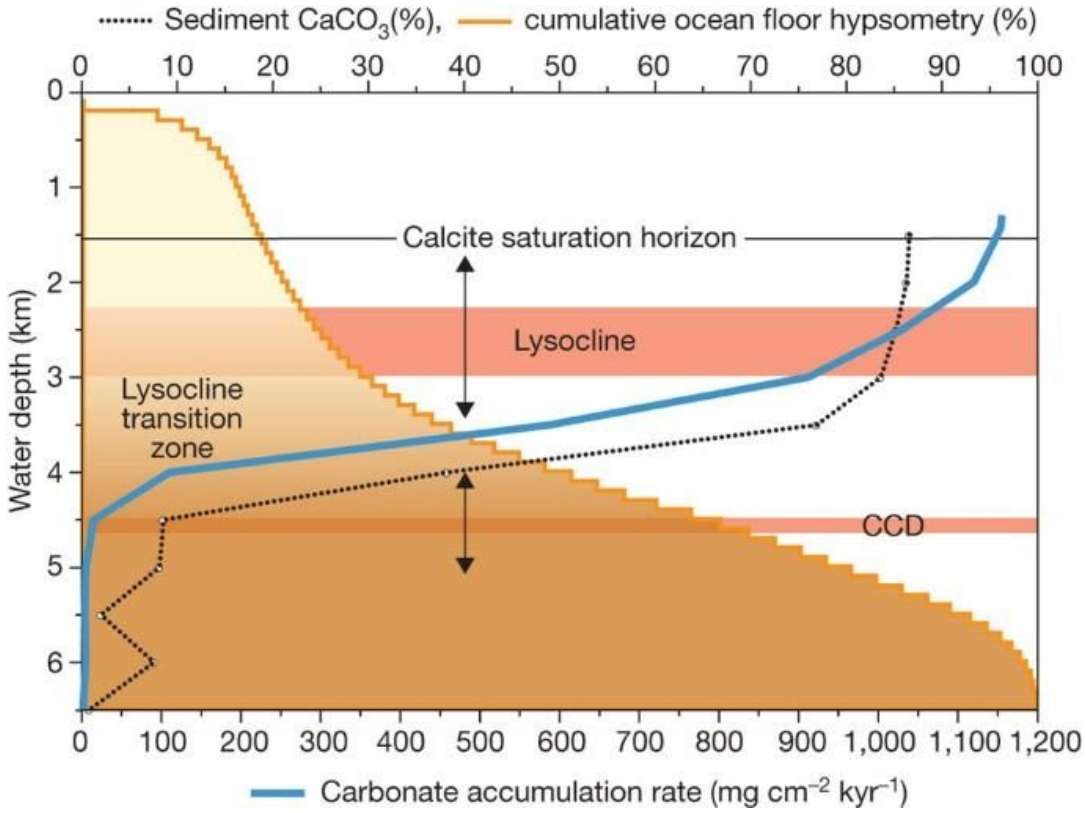
   ☐ Methane hydrates

   ☐ Deep-sea organisms

7. (6 points) Greater hydrothermal circulation has the effect of removing Mg from seawater, leading to a period of calcite seas. Explain **two** reasons for the marked increase in sea level when calcite seas are present.

   Solution: Calcite seas, which indicate relatively low Mg content in seawater, are mainly caused by an increase in tectonic activity (2 pts). Sea level rises because warmer and more buoyant oceanic lithosphere creates shallower ocean basins (2 pts) and more greenhouse gases are emitted into the atmosphere (2 pts).

9 Seafloor Sediments



Refer to the figure above for the next three questions.

1. (1 point) According to the diagram, at which approximate depth range does the rate of calcite dissolution increase most rapidly?

   A. 1.25 to 2 km

   B. 2 to 3 km

   C. 3 to 4 km

   D. 4 to 4.5 km

   E. 4.5 to 6.5 km

2. (1 point) According to the diagram, approximately what percent of sediment is composed of calcium carbonate at a depth of 3.5 km?

   A. 10-25

   B. 35-40

   C. 45-50

   D. 75-80

   E. 90-95

3. (1 point) Approximately what percentage of the seafloor exists at a depth below 2 km?

   A. 0

   B. 20

   C. 40

D. 60

E. 80

F. 100

4. (1½ points) Which of the following types of biogenous sediment would you expect to find at a depth of 5.5 km? Select all that apply.

A. Turbidites

B. Diatomaceous ooze

C. Stromatolites

D. Abyssal clay

E. Foraminiferal ooze

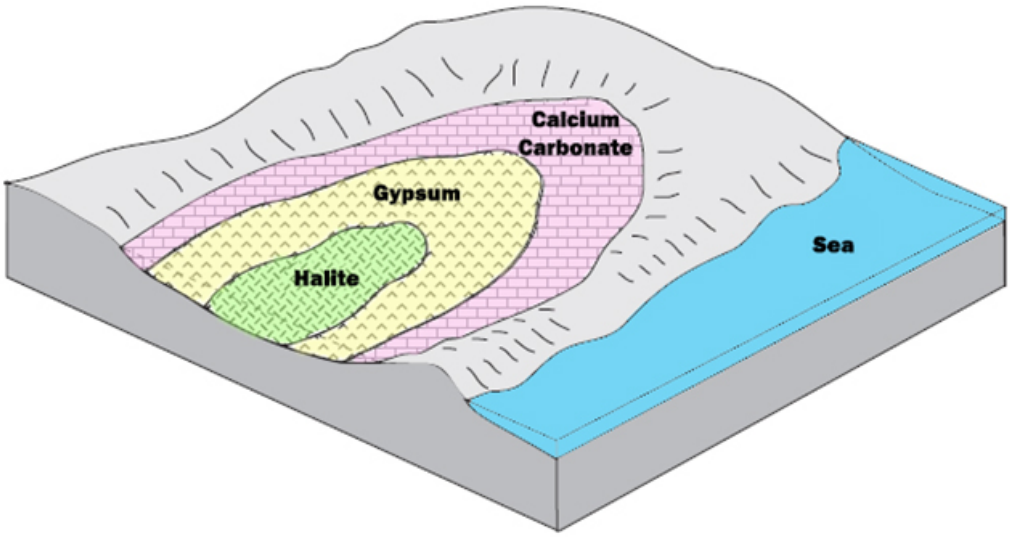
F. Radiolarian ooze

5. (4 points) If the rate of carbonate deposition is 275 $\mathrm{mg\,cm^{-2}\,kyr^{-1}}$ at a depth of 4 km, how many milligrams of carbonate per square centimeter is dissolved (destroyed) each year? Explain your answer. (*hint: read the data in the graph*)

Solution: Carbonate accumulation rate = carbonate deposition rate - carbonate dissolution rate (1 pt)

From the graph, carbonate accumulation rate at 4 km is approximately 100 $\mathrm{mg\,cm^{-2}\,kyr^{-1}}$. So, 100 = 275 - carbonate dissolution rate (1 pt)

carbonate dissolution rate = 275 - 100 = 175 $\mathrm{mg\,cm^{-2}\,kyr^{-1}}$ (1.75 pts) This means 175 mg per square centimeter every 1000 years, so the amount deposited every year is 175/1000 = $\boxed{0.175\mathrm{mg\,cm^{-2}\,kyr^{-1}}}$ (.25 pts)



6. (1 point) What classification of sediment is shown above?

A. Biogenous

B. Cosmogenous

C. Hydrogenous

D. Terrigenous

E. None of the above

7. (1 point) What classification of sediment is shown above, and where in the ocean would it form?

A. Biogenous, Continental Shelf

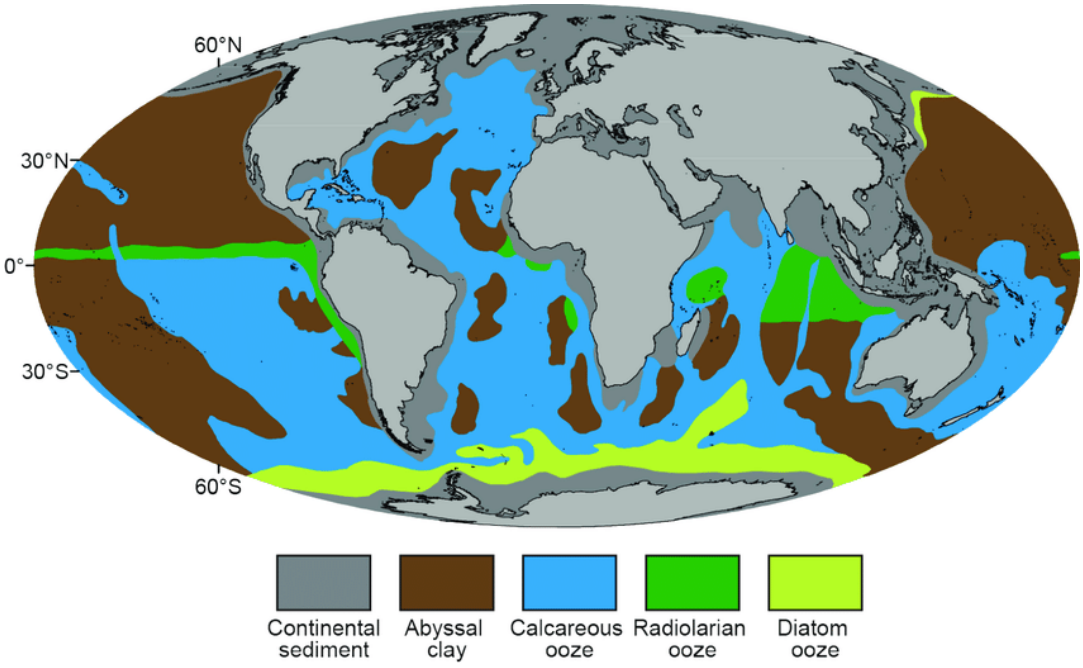
B. Biogenous, Abyssal Plain

C. Hydrogenous, Continental Shelf

D. Hydrogenous, Abyssal Plain

E. Terrigenous, Continental Shelf

F. Terrigenous, Abyssal Plain



8. (1 point) Which of the following sediment types dominates the North Pacific Ocean?

A. Abyssal clay

B. Continental sediment

C. Calcareous ooze

D. Radiolarian ooze

E. Diatom ooze

9. (1 point) Which of the following sediment types is found in the equatorial Pacific Ocean and is represented in the map by the dark green color?

A. Abyssal clay

B. Continental sediment

C. Calcareous ooze

D. Radiolarian ooze

E. Diatom ooze

10. (1 point) At which of the following locations would sediment accumulations be the thickest?

A. Western coast of North America

B. Eastern coast of South America

C. Center of the Atlantic Ocean Basin

D. South of the Pacific Ocean Basin

E. Southeast of the Indian Ocean Basin

10 Ocean Chemistry

1. (1 point) Which of the following sources represents the most significant influx of silicic acid into the oceans?

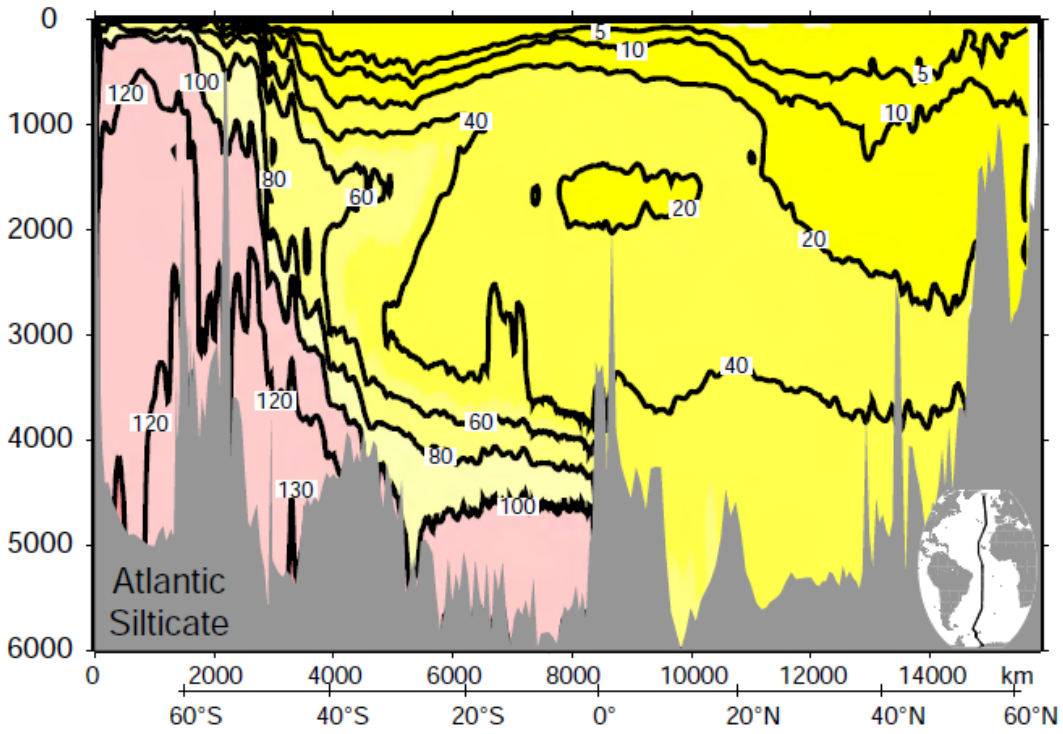
   A. Hydrothermal vents

   B. Biological output

   C. Rivers

   D. Windblown dust

   E. Glaciers

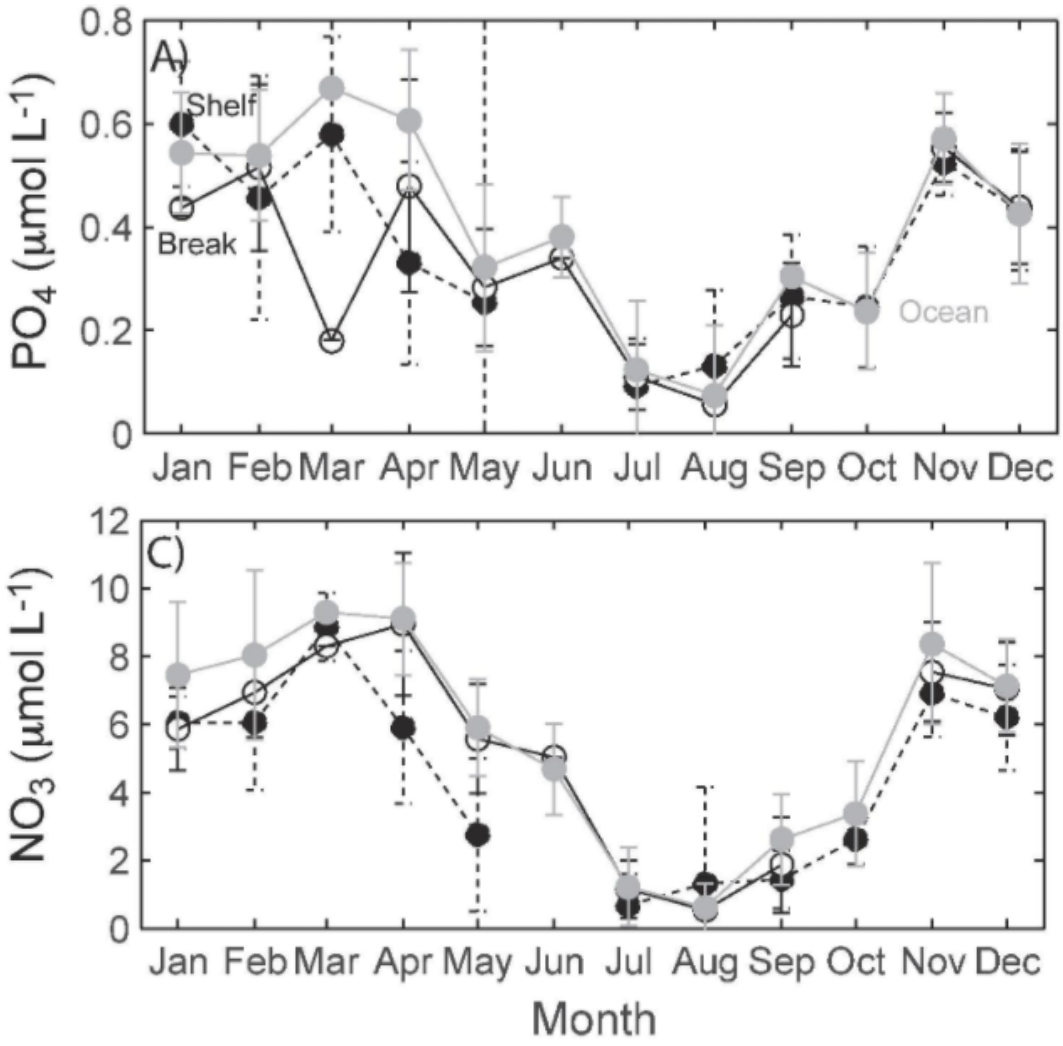


2. The figure above shows the dissolved silica profile (micromol/kg) in the Atlantic Ocean.

   (a) (2 points) ___**AABW**___ Which water mass is represented by the pink shading?

   (b) (4 points) Briefly explain why there exists a carbonate compensation depth but not a silicate compensation depth.

   Solution: Silica is (usually) saturated throughout the water column (2 pts, for equivalents too), while carbonate is saturated at the surface but undersaturated deeper down due to the increasing solubility of CO2 (2 pts). Or, if an explanation is given that there *is* a silica compensation depth, justification should be that it is usually not observed because it is too deep; in reality, this pretty much doesn't happen. (2 pts)



3. The graphs above show phosphate and nitrate concentrations off of the Hebrides Shelf as measured by Painter et al., 2017.

   (a) (3 points) Briefly explain the significance of the Redfield ratio. What is it, and why is it important?

   Solution: The Redfield ratio is typically expressed as a stoichiometric ratio between N, P, and C within ocean water (1.5 pts). It is generally accepted to be the nutrient balance for optimal phytoplankton growth (1.5 pts).

   (b) (3 points) Calculate N:P using the grey data points in April. Is this consistent with the Redfield ratio?

   Solution: P = 0.6 micromolar; N = 9 micromolar. 9/0.6 = 15. Hence, N:P = 15:1 (2 pts), which is relatively consistent with the Redfield ratio (1 pt).

11 Internal Waves and Mixing

1. The phase velocity of an internal gravity wave is given by

$$v = \sqrt{\frac{g\Delta\rho H_1 H_2}{\rho_0(H_1 + H_2)}} \tag{5}$$

Where ρ_0 is the reference density of the ocean, taken as $1020\,\mathrm{kg/m^3}$.

(a) (2 points) Calculate the phase velocity of an internal wave traveling between a surface layer of density 1022 $\mathrm{kg/m^3}$ and a bottom layer of 1025 $\mathrm{kg/m^3}$, given that the surface layer has a thickness of 80 meters and the bottom layer has a thickness of 680 meters.

Solution: We can find $\Delta\rho = 3$ $\mathrm{kg/m^3}$. Plugging in values, we find v = 1.44 m/s.

(b) (7 points) Show that the formula for internal gravity wave phase velocity reduces down to the formula for shallow-water gravity waves at the surface. (*Hint: make approximations when reasonable*)

Solution: The air-sea interface is indeed still a fluid interface; hence, "normal" gravity waves at the surface are still technically internal waves! $\Delta\rho$ is quite close to ρ_0, so $\Delta\rho/\rho_0$ is approximately 1 (2 pts). Next, taking H_1 to be the thickness of the atmosphere and H_2 to be the thickness of the shallow ocean, we know that $H_2 \gg H_1$ (2 pt). Thus, $(H_1 + H_2)$ is just about H_1, and the H_1 cancels out (2 pts). Hence, this reduces down to $v = \sqrt{gH_2}$, which is the formula for the speed of shallow water gravity waves! (1 pt)

(c) (2 points) Which of the following justifies why internal waves are generally observed to propagate along the thermocline?

A. The thermocline usually aligns with the pycnocline

B. Oceanic internal waves are only observed at steep temperature gradients

C. Ekman transport does not penetrate below the thermocline

D. The accumulation of planktonic exoskeletons at the thermocline creates a diffuse film

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2. The Richardson number, Ri, is a dimensionless quantity useful in describing internal wave dynamics, and is expressed as the ratio:

$$\mathrm{Ri} = \frac{N^2}{(\partial u/\partial z)^2} \tag{6}$$

$$N^2 = \frac{-g(\partial\rho/\partial z)}{\rho_0} \tag{7}$$

Where z is the *negative* depth (e.g. 100 m below sea level is $z = -100$) and ρ_0 is a *positive* reference density (usually taken as 1020 $\mathrm{kg/m^3}$).

(a) (4 points) Describe the mathematical condition necessary for N to be a real number. Give a physical interpretation for this condition.

Solution: Square rooting both sides, we see that $\partial\rho/\partial z$ must be negative (2 pts) for N to be a real number (to get a positive under the sqrt). Since z decreases with depth, this means that density must increase with depth (2 pt). This is essentially always true in the ocean.

(b) (4 points) What does N mean in this context? (*Hint: $\partial\rho/\partial z$ is the change in density over some change in depth*)

Solution: N (the Brunt-Vaisala frequency) describes the stability to disturbances based on the vertical density gradient (i.e. stratification) (2 pts). As the magnitude of $\partial\rho/\partial z$ increases (keep in mind that it must be negative for N to be a real number), this means that the density gradient is greater, with the bottom water having greater density than the surface water (2 pts). Intuitively, this means that the water will be quite stable to convection. (award +2 pt for any reasonable explanation)

(c) (8 points) If Ri is small for a column of water, would there be significant mixing? Justify your answer. (*Hint: u is horizontal velocity*)

Solution: When Ri is small, this either means that N^2 is small, or $\partial u/\partial z$ is large (2 pts). In the first case, N^2 is small if the water is not strongly stratified; hence prone to convective motions (2 pts). In the latter case, we have high vertical shear of velocity - intuitively, this would promote mixing as turbulence may develop along the density interface (2 pts). Hence, a small Richardson number is associated with large mixing. (2 pts)

(d) (4 points) Ocean mixing from internal waves may bring large amounts of phytoplankton into deeper waters. How might this affect nitrate and phosphate curves?

Solution: Phytoplankton must use nitrate and phosphate for metabolic functions (2 pts). Nitrate and phosphate are generally more concentrated in deep water due to lack of primary productivity. Hence, "downwelling" of phytoplankton causes a dip/flattening in the nitrate and phosphate curves (2 pts). Accept reasonable answers describing the effect on the curves over time (presumably the phytoplankton die, so the nitrate and phosphate will eventually be cycled up the food chain until it is released again in the form of waste/decomposing zooplankton).

12 Tides

1. (2 points) Interestingly, the period of a diurnal tide is 24 hours and 50 minutes. What is one change to the Earth-Moon-Sun system that would *increase* the period of diurnal tides?

   Solution: Decreasing the orbital period of the moon, or equivalent; decreasing rotation rate of earth.

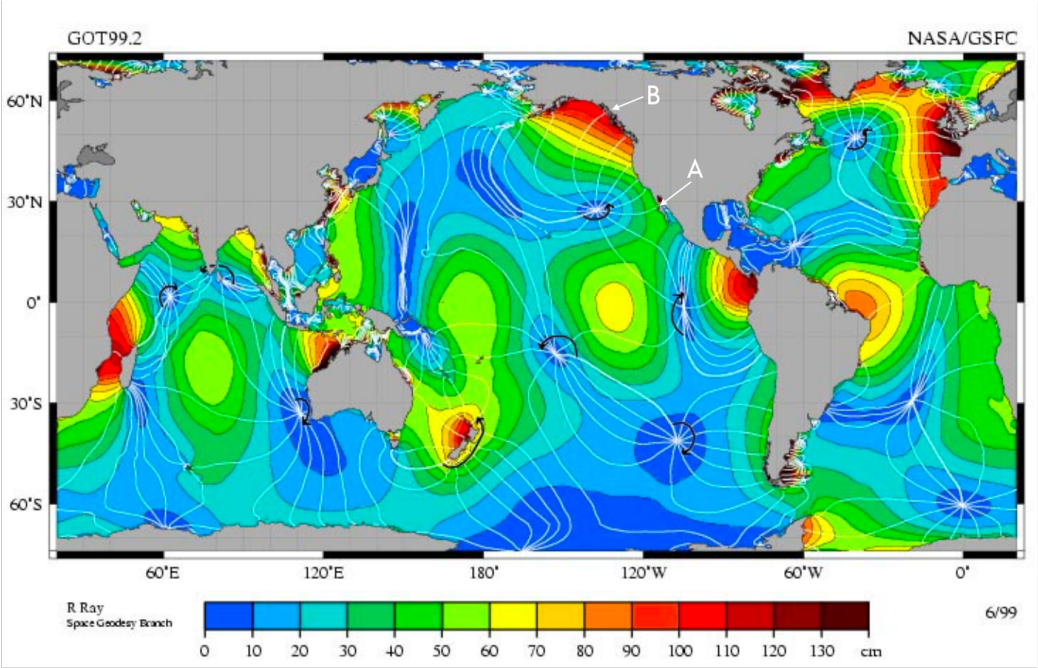
2. The levels of high tide and low tide vary with the interaction of a variety of tidal constituents. For each of the conditions below, determine whether the condition in isolation acts to increase, decrease, or does not affect tidal range.

   (a) (1½ points) **Increase** Moon at perigee

   (b) (1½ points) **Increase** A solar eclipse

   (c) (1½ points) **Increase** Moon coincides with the ecliptic

   (d) (1½ points) **No effect** Earth orbital speed increased



The figure above is a cotidal chart for the M2 tidal constituent, which accounts for the greatest height change within a given tidal range. Colors represent amplitude, and white lines are cotidal lines of equal phase.

3. (4 points) Which of the following does NOT affect the period of the M2 constituent? Choose all that apply:

   ■ **The period of Earth's orbit about the Sun**

   ☐ The period of Moon's orbit about the Earth

   ■ **The eccentricity of the Moon's orbit**

   ☐ The obliquity of Earth's rotation

   ■ **The Earth-Moon-Sun configuration**

4. (3 points) **5 hours** To the nearest hour, approximate the time interval between high tide at A and the high tide at B.

5. (8 points) What is the amplitude at amphidromic points as shown in the chart? Describe how this amplitude

differs from observed changes in sea surface height (SSH) due to tidal effects, and give a brief explanation as to why.

Solution: The amplitude shown is 0 cm (2 pts). However, the observed tidal range at these points is greater than 0 (2 pts) from the interaction of all tidal constituents (2 pts). The chart shown only depicts the M2 constituent (2 pts).

13 Wind-Driven Circulation

1. (1 point) If a northerly wind (i.e., blowing from the north) blows over a stretch of water in the Southern Hemisphere, in which cardinal direction will the net Ekman transport be?

   A. North

   B. South

   C. East

   D. West

2. (1 point) Which of the following processes is driven primarily by Ekman transport?

   A. Atlantic Meridional Overturning Circulation

   B. Coastal upwelling along California

   C. Slow horizontally-rotating vortices in alternating directions at the ocean surface

   D. Pacific Decadal Oscillation

3. Suppose an existing ocean gyre is no longer influenced by wind, and its surface currents gradually weaken until the entire gyre dissipates.

   (a) (4 points) Describe changes in the major forces acting on the surface currents that lead to the collapse of the gyre.

   Solution: The currents were initially in geostrophic balance with the pressure-gradient force/gravity balanced with the Coriolis effect (2 pts). Once isolated from wind frictional forces within the gyre allow the pressure-gradient force to dominate (1 pt). After geostrophic balance is no longer maintained, the PGF will also dissipate due to lack of wind (1 pt).

   (b) (4 points) In reality, gyres are able to sustain themselves. Identify their ultimate energy source, and explain how it drives gyre circulation and prevents their collapse.

   Solution: Radiation from the Sun is the ultimate energy source (1 pt). Surface currents are wind-driven (1 pt), and the winds responsible are a result of both latitudinal differences in heating from solar radiation (1 pt) and the Earth's rotation. Drag from the wind onto surface currents imparts the energy necessary to prevent friction/mixing/turbulence from disrupting geostrophic flow (1 pt).

4. Let's dive a bit deeper! In 1942, Sverdrup proposed that the lateral convergence and divergence of Ekman transport causes vertical movement in the water column.

   (a) (1 point) Convergence of Ekman transport causes **downwelling** and is known as Ekman **pumping**.

   (b) (2 points) In this model, identify the global prevailing winds that drive the subtropical gyres.

   Solution: Prevailing westerlies; trade winds (1 for each)

   (c) (4 points) Justify how Ekman transport leads to downwelling at the center of subtropical gyres.

   Solution: Geostrophic flow in a subtropical gyre is cyclonic (cw in the northern hemisphere) (1 pt). The Ekman transport thus points inwards toward the center of the gyre (1 pt) which leads to a surface convergence. This must cause a vertical (downwelling) motion at the center to compensate for the

horizontal motion (2 pts).

(d) (8 points) Five years after Sverdrup's original publication, he revised the wind-driven circulation model to account for internal wind-driven flow. Now, this is usually referred to as Sverdrup transport. Describe how lateral convergence or divergence of Ekman transport at the surface leads to an internal meridional (i.e. North-South direction) transport below the Ekman layer.

Solution: There is downwelling of water in a subtropical gyre. (2 pts) In a subpolar gyre, circulation is in the opposite direction; hence, there is upwelling of water at the center (2 pts). This "squashing" and "stretching" of the water column leads to a horizontal (more specifically, meridional) transport component, as the vertical transport must be compensated (4 pts). This is somewhat analogous to a circulation cell in the atmosphere.

(e) Let's try to mathematically formulate the description above. A useful equation here is the conservation of potential vorticity, which can be thought of as a conservation of angular momentum for fluids:

$$Q = \frac{(\zeta + f)}{H} \tag{8}$$

Where Q is the potential vorticity, ζ is the relative vorticity (think of this as the inherent rotation of the fluid parcel relative to the Earth's surface), f is the Coriolis parameter (think of this as the rotation of a fluid due to the rotation of the Earth), and H is the thickness of the fluid parcel.

$$f = 2\Omega \sin(\varphi) \tag{9}$$

Where Ω is the rotation rate of the Earth and φ is latitude.

i. (4 points) How does the magnitude of f change with latitude? Where is $|f|$ maximized, and where is it minimized?

Solution: The magnitude of f increases with increasing latitude (it is negative in the Southern Hemisphere) (2 pts). It is maximized at the poles and minimized at the equator (2 pts).

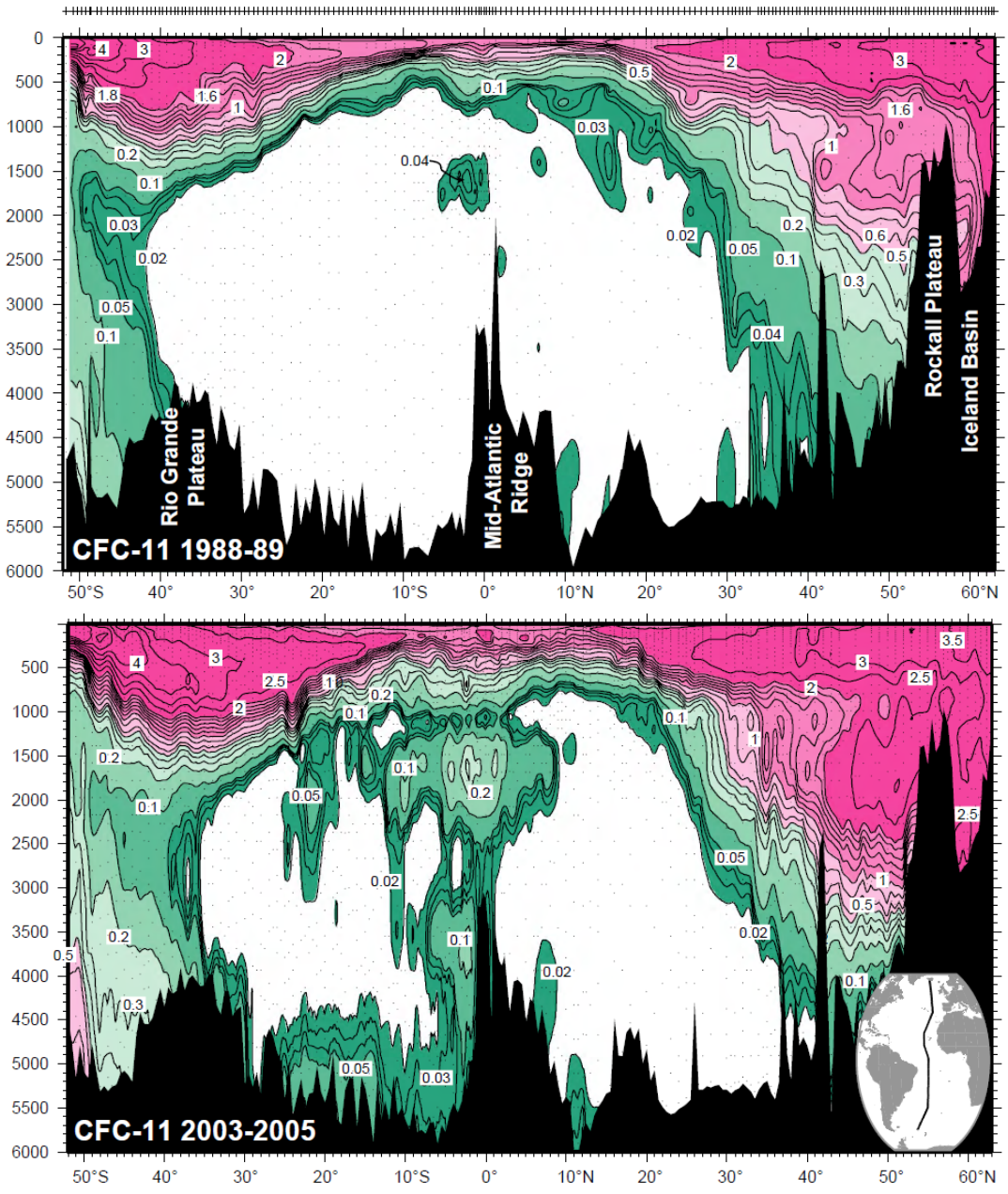
ii. (10 points) Using the conservation of potential vorticity, show that downwelling in subtropical gyres causes meridional transport. What assumption is necessary here, and is it reasonable? (*Hint: how does downwelling change water parcel thickness?*)

Solution: We need to show that Q is conserved, i.e. it does not change for such a process. There is a "squashing" of internal deep water for downwelling; hence, H decreases (2 pts). Thus, for Q to stay constant, either ζ or f must decrease (2 pts). We are asked to justify the meridional transport, which is manifested in a change in f (2 pts). This assumes that the change in ζ, or the relative vorticity, is negligible when compared to a change in the Coriolis parameter (3 pts). In the middle of the ocean, this is somewhat reasonable, because mid-ocean velocities are relatively small (1 pt). (give 0.5 points for a reasonable justification that this assumption is *not* valid)

iii. (3 points) In which meridional direction (i.e north or south) does the Sverdrup transport in the North Pacific Subtropical Gyre go? Briefly explain using the potential vorticity justification above.

Solution: As we establish above, H decreases for downwelling. Thus, there must be a decrease in f, and hence a southward transport (3 pts) for potential vorticity to be conserved.

14 Ocean overturning



The figures above show the chlorofluorocarbon-11 (CFC-11) concentration along 20-25 deg W in the Atlantic Ocean (the transect is shown in the inset map).

1. (2 points) Is CFC-11 a conservative tracer? Why or why not?

> **Solution:** CFC-11 is a conservative tracer, because it cannot be added or removed anywhere in the water column. (2 pts for correct explanation with answer)

2. Provide brief explanations to account for the following features of the 1988-1989 profile:

   (a) (6 points) There is no detectable CFC-11 in the equatorial ocean interior, but there is much more in the subpolar ocean interior.

Solution: The center of the profile is closer to the equator, at mid-depths. CFC-11 is an anthropogenic atmospheric gas; hence, its entrance into the ocean must only occur at the surface (2 pt). There has not been enough time for the ocean to mix to distribute CFC-11 into the interior at equatorial latitudes (2 pt). This is supported by the 2003-2005 profile, which shows much greater propagation. CFC-11 may propagate to deeper depths due to deep convection and deep water formation at the poles (2 pt).

(b) (3 points) The highest CFC-11 concentrations exist at the surface at subpolar latitudes.

Solution: Again, CFC-11 is a gas and can only enter at the surface (1 pt). Gas solubility generally increases with decreasing water temperature, so we can expect the greatest flux to be near the poles where the water is cold (2 pt).

3. (6 points) The March mixed layer depth (MMLD) in the Labrador Sea is often used to characterize the Atlantic Meridional Overturning Circulation (AMOC). Why does MMLD serve as a fingerprint of the AMOC? Use the CFC-11 profiles to justify your answer for full points.

Solution: An important arm of the AMOC is the deep convection (2 pt) of water in the Labrador and GIN (Greenland-Iceland-Norwegian) Seas, which is a driving component of overturning in the northern hemisphere. MMLD is a measure of the degree of deep convection (2 pt). The CFC-11 tracer shows the propagation (the MLD can be inferred from the figures) of water as a result of deep convection (2 pt).

4. (5 points) Briefly explain the relationship between AMOC and the carbon cycle. Give one example of feedback in this system.

Solution: AMOC cycles atmospheric CO2 and sequesters it into the deep ocean via overturning (3 pts). Accept any reasonable feedback; a relatively well-accepted one is that decrease in overturning decreases CO2 sequestration, which may warm the atmosphere to lead to greater decreases in overturning (2 pts). AMOC weakening is primarily driven by increases in sea surface temperature, which propagate deeper into the water column.